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Evaluating the Crop Water Stress Index and its correlation with latent heat and CO_2 fluxes over winter wheat and maize in the North China plain

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ABSTRACT

Plant water status is a key factor impacting crop growth and agricultural water management. Crop water stress may alter canopy temperature, the energy balance, transpiration, photosynthesis, canopy water use efficiency, and crop yield. The objective of this study was to calculate the Crop Water Stress Index (CWSI) from canopy temperature and energy balance measurements and evaluate the utility of CWSI to quantify water stress by comparing CWSI to latent heat and carbon dioxide (CO_2) flux measurements over canopies of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.). The experiment was conducted at the Yucheng Integrated Agricultural Experimental Station of the Chinese Academy of Sciences from 2003 to 2005. Latent heat and CO_2 fluxes (by eddy covariance), canopy and air temperature, relative humidity, net radiation, wind speed, and soil heat flux were averaged at half-hour intervals. Leaf area index and crop height were measured every 7 days. CWSI was calculated from measured canopy-air temperature differences using the Jackson method. Under high net radiation conditions (greater than 500 W m^{-2}), calculated values of minimum canopy-air temperature differences were similar to previously published empirically determined non-water-stressed baselines. Valid measures of CWSI were only obtained when canopy closure minimized the influence of viewed soil on infrared canopy temperature measurements (leaf area index was greater than 2.5 m^2 m^{-2}). Wheat and maize latent heat flux and canopy CO_2 flux generally decreased linearly with increases in CWSI when net radiation levels were greater than 300 W m^{-2}. The responses of latent heat flux and CO_2 flux to CWSI did not demonstrate a consistent relationship in wheat that would recommend it as a reliable water stress quantification tool. The responses of latent heat flux and CO_2 flux to CWSI were more consistent in maize, suggesting that CWSI could be useful in identifying and quantifying water stress conditions when net radiation was greater than 300 W m^{-2}. The results suggest that CWSI calculated by the Jackson method under varying solar radiation and wind speed conditions may be used for irrigation scheduling and agricultural water management of maize in irrigated agricultural regions, such as the North China Plain.

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1. Introduction

Canopy temperature is a part of the canopy energy balance. As solar radiation is absorbed by leaves, leaf temperatures increase. Leaf cooling takes place as some of the thermal energy drives transpirational water loss. Under water deficit conditions, stomata close in response to loss of turgor pressure (Kramer, 1983), causing a lowering of transpiration rate and an increase in canopy temperature. Idso et al. (1981) defined the Crop Water Stress Index (CWSI) based on the empirical linear relationship between mid-day canopy-air temperature difference and vapor pressure deficit under high net radiation, non-water-stressed conditions. The CWSI has been frequently used to quantify crop water stress based on canopy temperature over the past three decades (Gardner et al., 1992a), and has also been used for irrigation management (Nielsen and Gardner, 1987; Nielsen, 1990).

Jackson et al. (1981, 1988) revised Idso's CWSI definition using a theoretical analysis based on the canopy energy balance and the Penman–Monteith equation. Other researchers have modified the Jackson CWSI over the past two decades (Clawson et al., 1989; Jones, 1999; Alves and Pereira, 2000; Qiu et al., 2000). Also another water deficit index using remotely sensed spectral information has been proposed (Moran et al., 1994).

Irrigation scheduling based on CWSI for different crops in different regions has been documented (Nielsen and Gardner, 1987; Nielsen, 1990; Garrot et al., 1990; Ben-Asher et al., 1992;

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Yazar et al., 1999; Barnes et al., 2000; Alderfasi and Nielsen, 2001; Orta et al., 2003; Silva and Rao, 2005). In the North China Plain, Yuan et al. (2004) compared and evaluated the performance of three CWSI calculations, and found that the Jackson CWSI was the best for quantifying crop water stress in winter wheat.

CWSI quantifies the combined effects of soil water, atmospheric, and crop conditions on crop water status. Nielsen and Anderson (1989) reported strong relationships between CWSI and stomatal conductance, leaf water potential, leaf transpiration rate, available soil water, and leaf CO_2 exchange rate in sunflower (*Helianthus annuus* (L.)). However, studies of the relationships between CWSI and canopy CO_2 flux and water use efficiency for additional crops are needed to advance our understanding and management of crop water stress using the easily measured CWSI. Research about the relationship between CWSI and canopy CO_2 flux in agricultural fields is rarely reported. Therefore, the objectives of this study were to compute CWSI by the Jackson method from measured canopy temperatures and meteorological data in winter wheat and summer maize fields in the North China Plain, and to evaluate the utility of CWSI to quantify water stress by comparing CWSI to latent heat and CO_2 flux measurements.

2. Materials and methods

The field experiments were conducted at Yucheng Integrated Agricultural Experimental Station of the Chinese Academy of Sciences in the North China Plain, 350 km south of Beijing (latitude 36°57′N, longitude 116°36′E, 28 m above mean sea level) from 2003 to 2005. The soil type in the experimental area was silt loam. Yin (2005) reported volumetric water content at field capacity, saturated hydraulic conductivity, and bulk density of the 0–50 cm soil layer to be 0.440 $m^3\,m^{-3}$, 75 mm d^{-1}, and 1.50 g cm^{-3}, respectively. Respective values for the 50–100 cm layer were 0.447 $m^3\,m^{-3}$, 55 mm d^{-1}, and 1.51 g cm^{-3}. Respective values for the 100–140 cm layer were 0.426 $m^3\,m^{-3}$, 88 mm d^{-1}, and 1.54 g cm^{-3}. Table 1 gives values of mean monthly temperature and precipitation recorded at the study site and the longer-term means at a site 40 km southeast of the experimental site.

Measurements were made at the center of a 300 m × 300 m field where winter wheat was grown from October to June and summer maize from July to September each year. In all three years, the wheat variety 'Gaoyou No. 503' and the maize variety 'Yudan 22' were planted. Row spacing was 27 cm for wheat and 70 cm for maize, and row direction was north-south. Surrounding the experimental field was uniform farmland of crops at similar growth stages. There was a fetch of over 5000 m for winds from all directions during the crop growing season.

Latent heat and CO_2 fluxes were measured with an eddy covariance system installed at a height of 2.10 m above the soil surface for winter wheat and 3.30 m for summer maize. The system consisted of a fast response infrared gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA). Data were recorded with a datalogger (CR23X Campbell Scientific Inc., Logan, UT, USA) at a sampling frequency of 20 Hz for each channel. Average values were calculated and recorded every 30 min. A net radiometer (CNR1, Kipp & Zonen, Delft, The Netherlands) was also installed at a height of 2.10 m for winter wheat and 3.30 m for summer maize to measure incoming, reflected, and emitted components of shortwave and longwave radiation. Air temperature and relative humidity were measured with a temperature/humidity probe (HMP45C, Vaisala, Helsinki, Finland). Wind speed was measured with an anemometer (A100R, Vector Instruments, Rhyl, United Kingdom). Two soil heat flux plates (HFP01SC, Hukseflux, Delft, The Netherlands) were installed at 0.10 m below the soil surface at row and interrow positions. For more details about the eddy covariance system and the experimental site, see Lee et al. (2004), Wang et al. (2006), Xiao et al. (2006), and Li and Yu (2007). Because sensors in the eddy correlation system were greatly influenced by rainy weather, the data obtained during these anomalous days were excluded from evaluations with CWSI calculations.

Crop canopy temperature was measured continuously with an infrared thermometer (IRT) installed on a bracket of the eddy covariance system. The IRT was pointed south with a 45° downward angle from the horizontal, detecting radiation in the 8–14 μm waveband (Minolta/Land Cyclops Compac 3, Land Instruments International, AMTEK, Inc., Beijing, China). Calibration of the IRT was performed prior to measurements using a commercial blackbody surface (Everest Interscience Inc., Tuscon, AZ, USA). Canopy temperature was measured every minute with average values computed every 30 min. Data from 1230 to 1500 local time were selected for computation of CWSI and analysis as this is the time of day when crop water stress and vapor pressure deficit are most likely to be at maximum values (Gardner et al., 1992b). Restriction of the data to this time period also minimizes the influence of varying solar azimuthal position on measured canopy temperature (Nielsen et al., 1984).Twenty plants were harvested weekly from randomly selected locations. Leaves were removed and leaf area was measured with a leaf area meter (LI-3100, LI-COR Inc., Lincoln, NE, USA) to compute leaf area index (LAI). Crop height was also measured weekly. Daily values of crop height were obtained from the measured data by linear interpolation.

CWSI was computed following the method of Idso et al. (1981) as

$$CWSI = \frac{dT - dT_{min}}{dT_{max} - dT_{min}} \quad (1)$$

Table 1
Mean monthly temperature and precipitation at experimental site (Yucheng Integrated Agricultural Experiment Station) and long-term means at Jinan Meteorological Station (40 km southeast of experimental site).

Month	Mean monthly temperature (°C)				Mean monthly precipitation (mm)			
	2003	2004	2005	1951–2005	2003	2004	2005	1951–2005
January	-3.4	-1.5	-2.6	0.8	3	0	0	6
February	1.8	4.1	2.2	1.8	2	11	11	10
March	6.8	8.8	5.5	7.9	43	56	0	15
April	13.7	15.2	15.3	15.7	160	52	28	32
May	20.1	19.0	19.0	21.8	12	47	37	47
June	24.7	23.7	26.8	26.3	57	196	65	83
July	25.5	26.2	27.1	27.5	108	224	168	204
August	24.7	24.4	24.7	26.2	70	205	77	160
September	20.5	20.9	20.3	21.8	60	37	218	64
October	13.6	13.6	13.9	15.8	152	9	17	37
November	5.5	6.7	8.8	8.1	20	8	6	21
December	0.2	0.2	1.9	1.3	11	2	1	8

where dT, dT_{max} and dT_{min} are actual, maximum, and minimum canopy-air temperature differences, respectively. The determinations of dT_{max} and dT_{min} are critical to computing CWSI. The value of dT_{max} was empirically set as 3 °C for winter wheat based on the observations for canopy-air temperature difference in the current research although previously reported research generally used 2 °C (Idso et al., 1981; Howell et al., 1986; Alderfasi and Nielsen, 2001). Values of dT_{max} are not really constant and probably vary primarily with net radiation and wind speed. For summer maize, the value of dT_{max} was also set to 3 °C (Nielsen and Gardner, 1987). dT_{min} was computed theoretically based on Jackson et al. (1981)

$$dT_{min} = \frac{r_a(R_n - G)}{\rho C_p}\,\frac{\gamma(1 + r_{cp}/r_a)}{\Delta + \gamma(1 + r_{cp}/r_a)} - \frac{VPD}{\Delta + \gamma(1 + r_{cp}/r_a)} \qquad (2)$$

where R_n is the net radiation, G is the soil heat flux, ρ is the air density, C_p is the specific heat at constant pressure, γ is the psychometric constant, Δ is the slope of the saturated vapor pressure–temperature curve, r_a is the aerodynamic resistance, r_{cp} is the canopy resistance at potential transpiration, and VPD is the vapor pressure deficit. r_{cp} was set as 22.7 s m^{-1} for winter wheat, an average value from the research by Yuan et al. (2004) and 25.0 s m^{-1} for summer maize (Steduto and Hsaio, 1998). The aerodynamic resistance can be computed by (Thom and Oliver, 1977)

$$r_a = \frac{4.72(\ln((z - d)/z_0))^2}{1 + 0.54u} \qquad (3)$$

where z is the reference height, d is the displacement height, z_0 is the roughness length, and u is the wind speed. The terms z_0 and d can be represented as functions of the crop height, h. In the current study, $d = 0.56$ h and $z_0 = 0.13$ h (relationships given by Legg and Long, 1975).

Water use efficiency is an important parameter in crop simulation models and yield estimation. It has different definitions depending on the time and space scales of the processes and system aggregation it refers to (Steduto, 1996). Canopy water use efficiency (CWUE) in this study was defined as

$$CWUE = \frac{Fc}{E} \qquad (4)$$

where Fc = CO_2 flux over the canopy; $E = H_2O$ flux over the canopy = latent heat flux/latent heat of vaporization.

3. Results and discussion

3.1. Verifying dT_{min}

Because of the critical influence that dT_{min} has on the calculation of CWSI, we used observed meteorological data collected between 1230 and 1500 local time when net radiation was greater than 500 W m^{-2} to verify that energy balance instrumentation were functioning properly and formulas used to calculate dT_{min} (Eqs. (2) and (3)) were properly implemented. The data observation times were restricted to high net radiation periods when full canopy cover was assured so that the calculated dT_{min} values could be compared to previously published empirically derived non-water-stressed baselines that had also been determined under high net radiation conditions (Idso, 1982; Nielsen and Gardner, 1987). Data were averaged by 0.25 kPa VPD classes to smooth the data. The data for both wheat and maize indicate some variation from the previously published empirically established non-water-stressed baselines (Fig. 1), but are sufficiently close to give us confidence in using the Jackson method to calculate dT_{min} from the energy balance components. Values of dT_{min} declined linearly from about 2 to −5 °C as VPD increased

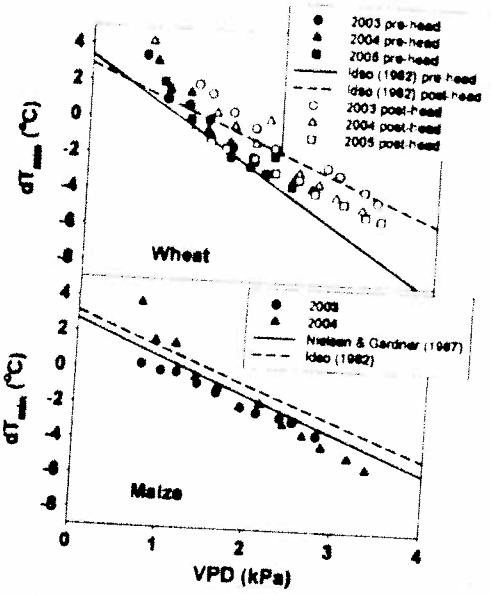

Fig. 1. Relationship between vapor pressure deficit (VPD) and minimum canopy-air temperature difference (dT_{min}) as calculated by Eq. (2) (Jackson energy balance method) over wheat and maize canopies. The data points are from half-hourly average values taken between 1230 and 1500 when net radiation was greater than 500 W m^{-2}.

from 1 to 3.5 kPa for both wheat and maize under high net radiation conditions.

Fig. 2 (2003 maize) is shown as an example of how dT_{min} under non-water-stressed conditions increases as net radiation increases, but the slope of the linear decrease with increasing VPD remains essentially unchanged. At a VPD of 2 kPa, dT_{min} is −3.8 °C when net radiation is between 100 and 200 W m^{-2}, and −2.9 °C when net radiation is between 600 and 700 W m^{-2}.

3.2. Influence of leaf area development on CWSI

CWSI for both wheat and maize fluctuated widely for both wheat and maize crops early in the growing season of each crop, and often exceeded the theoretical maximum value of 1.0 (Fig. 3). This was primarily caused by the IRT viewing the warm

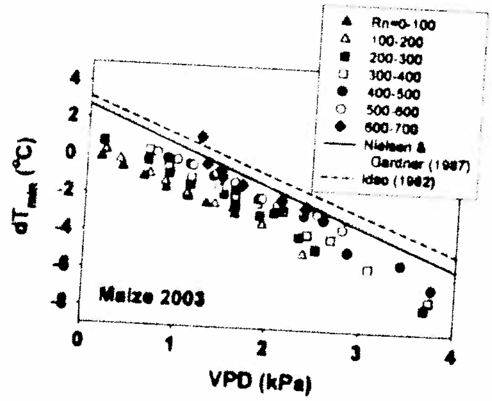

Fig. 2. Relationship between vapor pressure deficit (VPD) and minimum canopy-air temperature difference (dT_{min}) as calculated by Eq. (2) (Jackson energy balance method) over a maize canopy in 2003. The data points are from half-hourly average values taken between 1230 and 1500 and are separated by net radiation class.

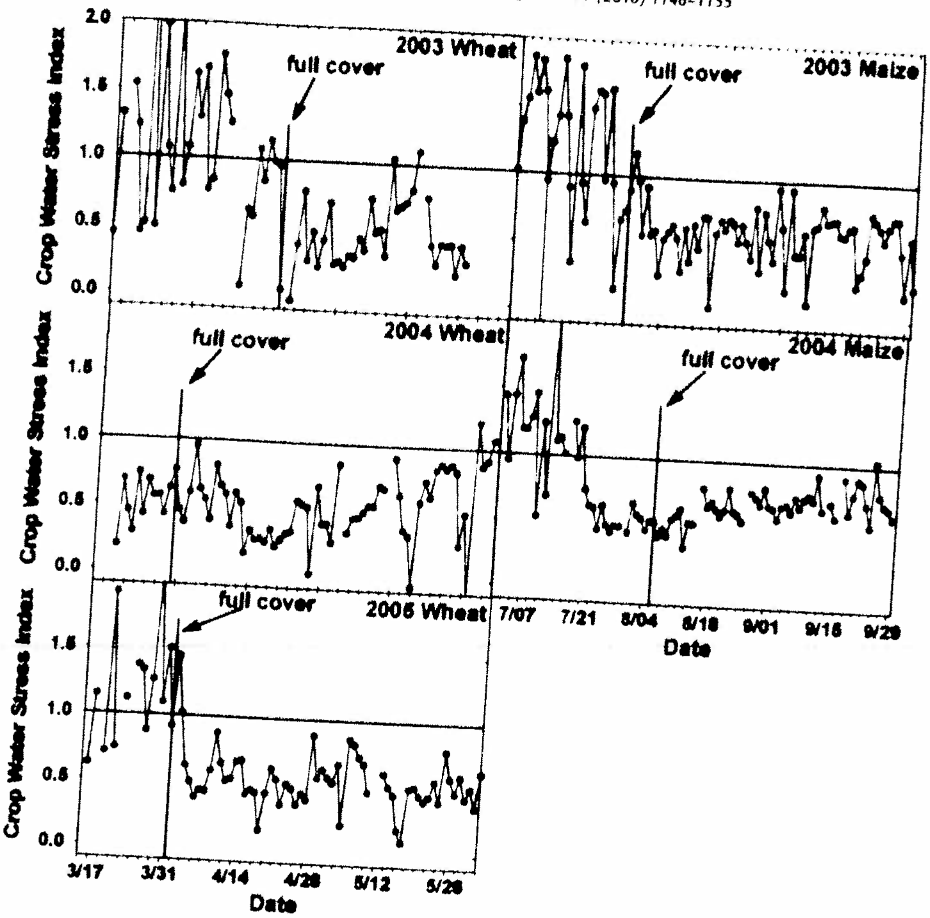

Fig. 3. Crop Water Stress Index for wheat (2003–2005) and maize (2003–2004).

soil surface between rows prior to canopy closure or full cover conditions, which we assumed to occur at LAI = 2.5 (Fig. 4). Early in the growing season, when LAI < 2.5, precautions should be taken to ensure that only vegetative material is viewed by the IRT to avoid the influence of a warm soil surface (Gardner et al., 1992a). Date of full cover for both crops varied between years (approximately 15 April in 2003 and 1 April in 2004 and 2005 for wheat; approximately 25 July in 2003 and 6 August in 2004 for maize). We therefore restricted our data set for further analysis to measurements made after full cover development.

3.3. Relationship between latent heat flux, CWSI, and net radiation

To investigate the relationship between CWSI and LE (and canopy photosynthesis and canopy water use efficiency, discussed later) we again restricted the data used for analysis to data collected after full cover and between 1230 and 1500 local time. Data were averaged by 0.10 kPa VPD classes to smooth the data. For both wheat and maize, when the relationship between CWSI and LE is considered regardless of net radiation level (Fig. 5, upper left panel), there appears to be no correlation. But as the data are separated into net radiation classes the negative relationship between LE and CWSI becomes apparent at net radiation levels greater than 300 W m^{-2} (Fig. 5, lower two panels). Similar relationships were found for wheat in 2004 and 2005 and for maize in 2003 and 2004 (data not shown). Significant negative linear relationships between LE and CWSI were found when net radiation was greater than 300 W m^{-2} for wheat in 2003 and 2004 and for maize in 2003, and also for maize in 2004 when net radiation was greater than 500 W m^{-2} (Table 2).

A significant increasing linear relationship between LE and CWSI was noted for maize in 2003 when net radiation was less than 100 W m^{-2}. In the other data sets under low net radiation conditions there was no significant relationship between LE and CWSI. Under these low net radiation conditions, LE is apparently more influenced by net radiation level or air temperature than by water availability.

Fig. 5 demonstrates that LE is related to both CWSI and Rn. At CWSI = 0.6, for example, LE = 200 W m^{-2} when Rn is between 300 and 400 W m^{-2}, while LE = 300 W m^{-2} when Rn is greater than 500 W m^{-2}. We further investigated the dependence of LE on CWSI and Rn by fitting the model

$$LE = a + b \times Rn + c \times CWSI + d \times Rn \times CWSI \tag{5}$$

to the data sets identified as significant in Table 2. Fig. 6 and Table 3 demonstrate the significant correlation between LE and both Rn and CWSI. The regression of LE on Rn, CWSI and the interaction of Rn and CWSI was highly significant ($P < 0.01$) for all five crop/year combinations. Correlation coefficients ranged from 0.77 to 0.87 (Table 3). Values of LE predicted by the multiple linear regression given in Table 3 are plotted against observed values to demonstrate

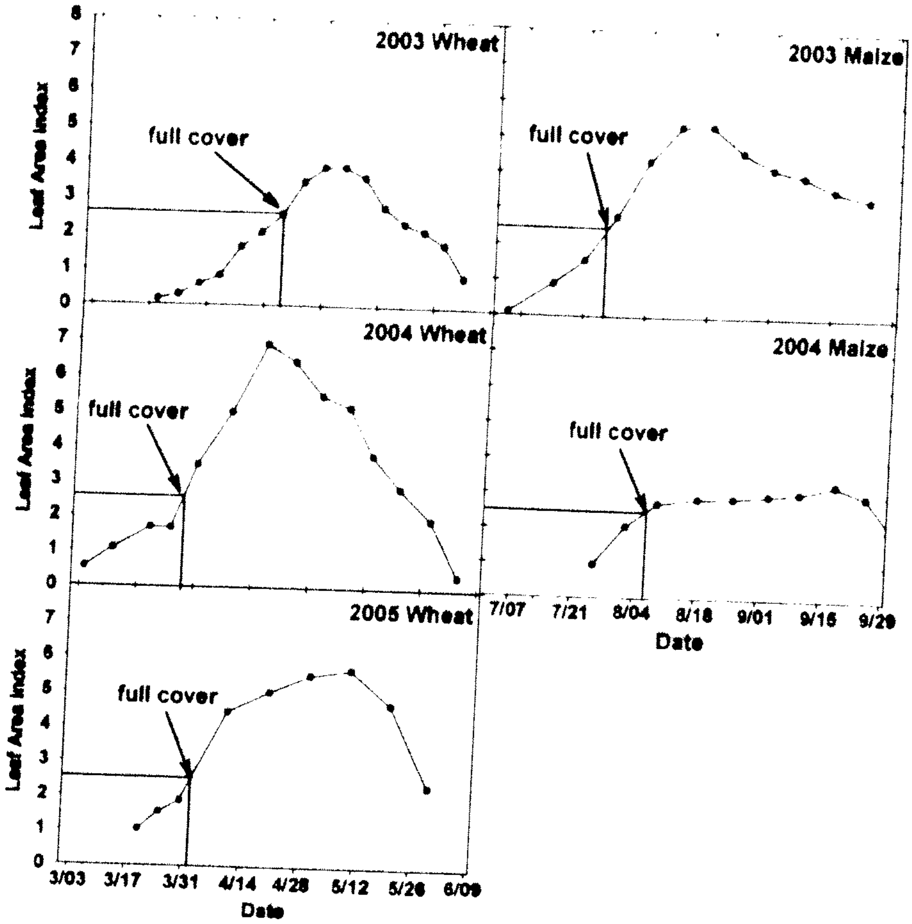

Fig. 4. Winter wheat and maize leaf area index development from 2003 to 2005.

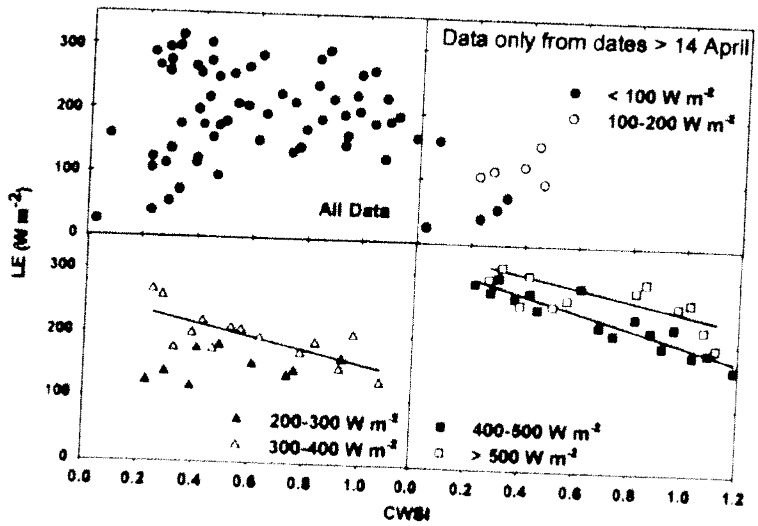

Fig. 5. Relationship between Crop Water Stress Index (CWSI) and latent heat flux (LE) for winter wheat on the North China Plain, 2003. Data are from half-hourly values from 1230 to 1500 local time that were then averaged by 0.1 CWSI classes and separated by net radiation class.

the correlation. Some of the scatter seen in Fig. 6 may be attributed to the fact that CWSI and Rn are single point measurements whereas the LE measurement integrates conditions over a large area that may have some spatial variability in water availability to plants.

3.4. Relationship between CO_2 flux, CWSI, and net radiation

Under water stress conditions, canopy conductance decreases, thereby restricting CO_2 flux (Olioso et al., 1996; Yu and Wang, 1998; Shangguan et al., 2000; Yu et al., 2004). CO_2 flux showed a

Table 2
Linear regression slope, intercept, R, and P values for model $LE = a + b \times CWSI$ (LE = latent heat flux ($W\,m^{-2}$), CWSI = crop water stress index).

Crop	Year	Net radiation class ($W\,m^{-2}$)	Slope	Intercept	R	P	N
Wheat	2003	0–100	−80.68	85.81	0.20	0.79	5
		100–200	65.70	95.87	0.31	0.62	5
		200–300	26.60	133.18	0.28	0.46	9
		300–400	**99.28**	**254.82**	**0.72**	**0.01**	**14**
		400–500	**124.07**	**321.48**	**0.92**	**0.01**	**19**
		>500	**93.82**	**340.00**	**0.57**	**0.04**	**13**
	2004	0–100	30.85	36.75	0.34	0.37	9
		100–200	6.40	97.85	0.03	0.94	8
		200–300	185.71	229.10	0.68	0.15	6
		300–400	6.60	201.43	0.05	0.85	17
		400–500	**−77.88**	**316.00**	**0.52**	**0.05**	**18**
		>500	**141.56**	**423.36**	**0.80**	**0.01**	**10**
	2005	0–100	94.96	96.37	0.60	0.40	4
		100–200	−21.49	140.19	0.09	0.79	11
		200–300	**180.73**	**286.32**	**0.82**	**0.01**	**10**
		300–400	**212.03**	**352.42**	**0.80**	**0.01**	**12**
		400–500	**148.10**	**388.84**	**0.88**	**0.01**	**14**
		>500	1.95	342.50	0.01	0.96	15
Maize	2003	**0–100**	**179.38**	**38.65**	**0.80**	**<0.01**	**15**
		100–200	−5.91	92.99	−0.04	0.90	14
		200–300	203.47	51.32	0.48	0.23	8
		300–400	**213.17**	**361.28**	**0.83**	**0.02**	**7**
		400–500	**166.86**	**378.77**	**0.67**	**0.02**	**9**
		>500	**296.88**	**404.20**	**0.80**	**<0.01**	**11**
	2004	0–100	−27.433	78.13	0.13	0.74	9
		100–200	41.80	79.28	0.25	0.39	14
		200–300	32.49	108.10	0.26	0.42	12
		300–400	2.51	179.34	0.02	0.95	11
		400–500	**81.92**	**287.87**	**0.78**	**<0.01**	**12**
		>500	**85.21**	**333.92**	**0.88**	**0.01**	**13**

R = correlation coefficient; P = probability that the null hypothesis of regression slope = 0 is true; N = number of observations; bold values indicate data sets when $P < 0.10$.

Table 3
Multiple linear regression coefficients for latent heat flux (LE), CO_2 flux (Fc), or canopy water use efficiency (CWUE) regressed against crop water stress index (CWSI) and net radiation (Rn) for wheat and maize canopies on the North China Plain.

Crop & year	N	Rn ($W\,m^{-2}$)	a	b	c	d	R	P
LE								
Wheat 2003	43	>300	115.3	0.4173	−119.1	0.0254	0.85	<0.01
Wheat 2004	31	>400	−124.3	0.9841	186.4	−0.5893	0.77	<0.01
Wheat 2005	40	>300	350.2	0.0405	498.5	0.7863	0.83	<0.01
Maize 2003	29	>300	−61.5	1.0089	223.7	−0.9304	0.83	<0.01
Maize 2004	24	>400	108.1	0.4000	68.6	0.0299	0.87	<0.01
Fc								
Wheat 2003	57	>200	0.8989	4.85E−04	−1.169	1.09E−03	0.64	<0.01
Wheat 2004	54	>300	1.0810	4.05E−04	0.561	−5.32E−04	0.70	<0.01
Wheat 2005	51	>200	0.1350	0.0200	0.4274	−1.12E−03	0.56	<0.01
Maize 2003	35	>200	1.0873	0.00180	−1.6048	1.17E−03	0.84	<0.01
Maize 2004	48	>200	0.9281	0.00204	0.8834	−6.30E−04	0.79	<0.01
CWUE								
Wheat 2003	43	>300	0.0157	−3.72E−06	0.0148	1.41E−05	0.18	0.71
Wheat 2004	54	>300	0.0259	−2.93E−05	0.0228	3.26E−05	0.64	<0.01
Wheat 2005	41	>300	0.0007	1.52E−05	0.0300	−5.35E−05	0.53	<0.01
Maize 2003	37	>200	0.0441	−7.10E−05	−0.0532	1.14E−04	0.63	<0.01
Maize 2004	48	>200	0.0402	−4.17E−05	0.0338	4.49E−05	0.84	<0.01

N = number of observations; a, b, c, d = linear regression coefficients for LE, Fc, or $CWUE = a + b \times Rn + c \times CWSI + d \times Rn \times CWSI$; R = correlation coefficient; P = probability that the null hypothesis that the multiple linear regression equation is not significant is true.

similar response to CWSI as previously described for LE (Table 4). CO_2 flux of wheat in 2003 and 2005 and of maize in 2003 increased with increases in CWSI when net radiation was very low (Rn < 100 $W\,m^{-2}$), and did not respond to CWSI when net radiation was very low in the other two crop-year data sets. As postulated earlier, this is probably a response of photosynthesis rate being more influenced by increasing temperature at low net radiation than by level of water stress. For wheat in 2003 at net radiation levels greater than 200 $W\,m^{-2}$ CO_2 flux declined with increasing CWSI. The negative response of CO_2 flux to increasing CWSI was not evident in wheat in 2004 until net radiation was greater than 300 $W\,m^{-2}$, and was not seen at all in wheat in 2005. For maize in both 2003 and 2004, CO_2 flux declined linearly with increases in CWSI at net radiation levels greater than 200 $W\,m^{-2}$ (2003) and greater than 100 $W\,m^{-2}$ (2004). Similar to the data shown in Fig. 5 for LE response to CWSI, higher levels of net radiation resulted in higher levels of CO_2 flux at a given CWSI level (data not shown).

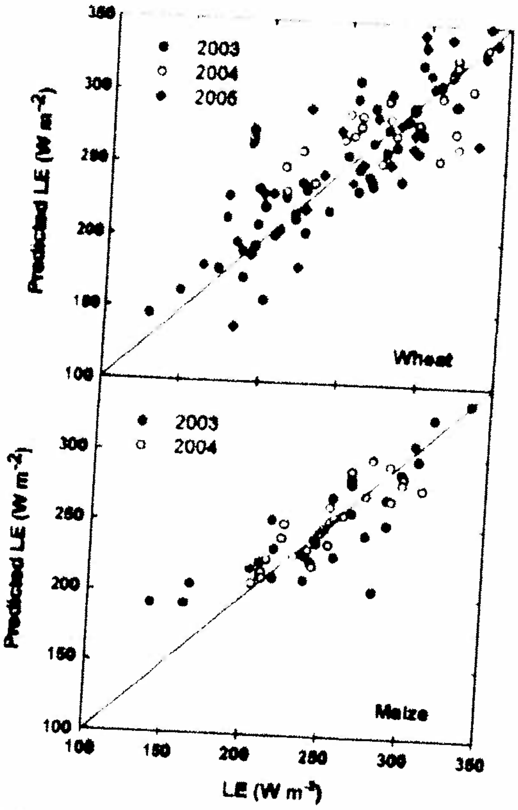

Fig. 6. Comparison of observed latent heat flux (LE) over wheat and maize with values of LE predicted by multiple linear regressions given in Table 3 using values of crop water stress index and net radiation.

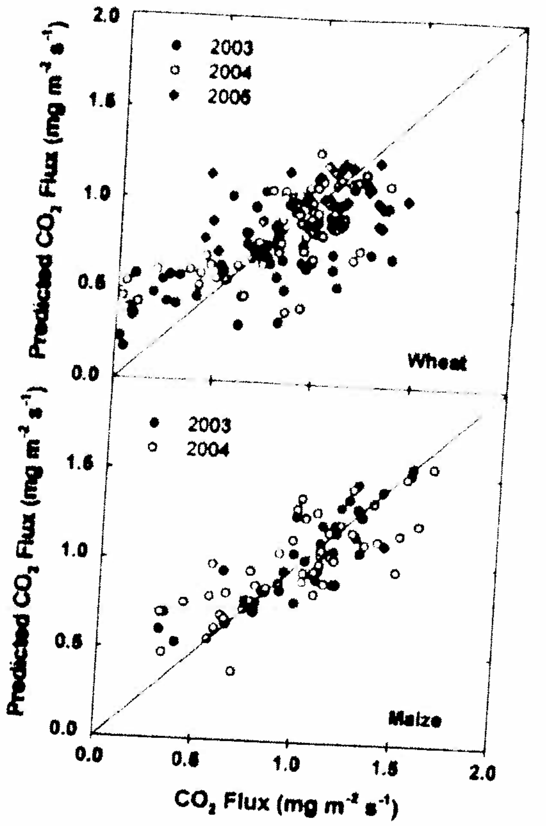

Fig. 7. Comparison of observed CO_2 flux (Fc) over wheat and maize with values of Fc predicted by multiple linear regressions given in Table 3 using values of crop water stress index and net radiation.

Table 4
Linear regression slope, intercept, *R*, and *P* values for model Fc = *a* + *b* × CWSI (Fc = CO_2 flux (mg m^{-2} s^{-1}), CWSI = crop water stress index).

Crop	Year	Net radiation class (W m^{-2})	Slope	Intercept	*R*	*P*	*N*
Wheat	2003	**0–100**	**1.530**	**0.235**	**0.96**	**<0.01**	**5**
		100–200	0.646	0.265	0.45	0.45	5
		200–300	**0.808**	**1.012**	**0.83**	**0.07**	**9**
		300–400	**0.847**	**1.068**	**0.72**	**<0.01**	**14**
		400–500	**0.641**	**1.096**	**0.59**	**<0.01**	**19**
		>500	**0.683**	**1.220**	**0.52**	**0.07**	**13**
	2004	0–100	0.173	0.124	0.21	0.59	9
		100–200	0.146	0.387	0.08	0.85	8
		200–300	0.454	0.907	0.46	0.35	6
		300–400	**0.810**	**1.257**	**0.63**	**0.07**	**17**
		400–500	**0.711**	**1.206**	**0.68**	**<0.01**	**18**
		>500	**0.898**	**1.332**	**0.77**	**<0.01**	**19**
	2005	**0–100**	**0.862**	**0.019**	**0.98**	**0.04**	**4**
		100–200	0.208	0.403	0.23	0.50	11
		200–300	0.254	0.459	0.25	0.48	10
		300–400	0.333	1.173	0.34	0.29	12
		400–500	0.308	1.285	0.30	0.30	14
		>500	0.049	1.034	0.05	0.85	15
Maize	2003	**0–100**	**1.282**	**0.063**	**0.88**	**<0.01**	**15**
		100–200	0.098	0.253	0.13	0.67	14
		200–300	**1.754**	**1.740**	**0.70**	**0.05**	**8**
		300–400	**2.433**	**2.570**	**0.90**	**<0.01**	**7**
		400–500	**0.594**	**1.649**	**0.60**	**0.09**	**9**
		>500	**1.023**	**2.030**	**0.86**	**<0.01**	**11**
	2004	0–100	0.115	0.308	0.10	0.80	9
		100–200	**0.519**	**0.617**	**0.53**	**0.06**	**14**
		200–300	**0.671**	**1.186**	**0.68**	**0.01**	**12**
		300–400	**1.557**	**1.982**	**0.94**	**0.01**	**11**
		400–500	**1.918**	**2.403**	**0.88**	**<0.01**	**12**
		>500	**0.730**	**1.687**	**0.53**	**0.06**	**13**

R = correlation coefficient; *P* = probability that the null hypothesis of regression slope = 0 is true; *N* = number of observations; bold values indicate data sets when $P < 0.10$.

Table 5
Linear regression slope, intercept, R, and P values for model CWUE = a + b × CWSI (CWUE = canopy water use efficiency (mg CO_2 per mg H_2O), CWSI = crop water stress index).

Crop	Year	Net radiation class ($W\,m^{-2}$)	Slope	Intercept	R	P	N
Wheat	2003	0–100	0.0264	0.0156	0.30	0.83	5
		100–200	0.0062	0.0100	0.18	0.78	5
		200–300	0.0224	0.0028	0.45	0.23	9
		300–400	**0.0101**	**0.0128**	**0.70**	**0.01**	**14**
		400–500	0.0111	0.0194	0.16	0.34	16
		>500	**0.0054**	**0.0108**	**0.54**	**0.07**	**13**
	2004	0–100	0.0434	0.0292	0.16	0.67	9
		100–200	0.0065	0.0060	0.13	0.76	8
		200–300	0.0018	0.0111	0.13	0.81	6
		300–400	**0.0108**	**0.0153**	**0.57**	**0.02**	**17**
		400–500	**0.0084**	**0.0133**	**0.65**	**0.01**	**18**
		>500	**0.0043**	**0.0083**	**0.58**	**0.01**	**19**
	2005	**0–100**	**0.0398**	**0.0029**	**0.98**	**0.01**	**4**
		100–200	**0.0118**	**0.0030**	**0.77**	**0.01**	**11**
		200–300	**0.0138**	**0.0015**	**0.78**	**0.01**	**10**
		300–400	0.0124	0.0041	0.42	0.17	12
		400–500	0.0024	0.0077	0.22	0.45	14
		>500	0.0000	0.0077	0.00	1.00	15
Maize	2003	0–100	0.0070	0.0221	0.07	0.79	15
		100–200	0.0178	0.0187	0.26	0.36	14
		200–300	**0.0352**	**0.0323**	**0.82**	**0.01**	**8**
		300–400	**0.0213**	**0.0248**	**0.87**	**0.01**	**7**
		400–500	0.0049	0.0079	0.37	0.27	11
		>500	0.0055	0.0076	0.51	0.11	11
	2004	0–100	0.0186	0.0052	0.08	0.83	9
		100–200	**0.0122**	**0.0158**	**0.58**	**0.03**	**14**
		200–300	**0.0182**	**0.0271**	**0.74**	**0.01**	**12**
		300–400	**0.0228**	**0.0288**	**0.98**	**0.01**	**11**
		400–500	**0.0207**	**0.0261**	**0.88**	**0.01**	**12**
		>500	-0.0037	0.0133	-0.31	0.30	13

R = correlation coefficient; P = probability that the null hypothesis of regression slope = 0 is true; N = number of observations; bold values indicate data sets when $P < 0.10$.

As was done for the evaluation of LE related to net radiation and CWSI, values of CO_2 flux were fit to the model given in Eq. (5), and the regressions (Table 3) were used to determine predicted CO_2 flux values which were plotted against the observed values (Fig. 7). Significant correlations were found between CO_2 flux and both Rn and CWSI. The regression of LE on Rn, CWSI and the interaction of Rn and CWSI was highly significant ($P < 0.01$) for all five crop/year combinations. Correlation coefficients ranged from 0.56 to 0.84 (Table 3). As with LE, we attribute some of the scatter seen in Fig. 7 to the fact that CWSI and Rn are single point measurements whereas the CO_2 flux measurement integrates conditions over a large area that may have some spatial variability in water availability to plants.

3.5. Relationship between CWSI and CWUE

CWUE for wheat in 2003 was not affected by CWSI except when net radiation level was less 300–400 $W\,m^{-2}$ and greater than 500 $W\,m^{-2}$ (Table 5). At those net radiation levels there was a decline in CWUE with increasing CWSI. A similar result was seen for wheat in 2004 when net radiation was greater than 300 $W\,m^{-2}$. CWUE increased with increasing water stress for wheat in 2005 up to a net radiation level of 400 $W\,m^{-2}$. At greater net radiation levels in that year there was no response of CWUE to increasing water stress. For maize there was a fairly well defined decrease in CWUE with increasing water stress in both 2003 and 2004 when net radiation was between 200 and 400, and in 2004 for net radiation between 100 and 500 $W\,m^{-2}$. For net radiation greater than 400 $W\,m^{-2}$ in 2003 and greater than 500 $W\,m^{-2}$ in 2004 there was no change in CWUE with increasing CWSI. Previous research reported wheat water use efficiency declined with increases CWSI (Wang et al., 2005).

Application of the regression model given in equation 5 to the wheat data when net radiation was greater than 300 $W\,m^{-2}$

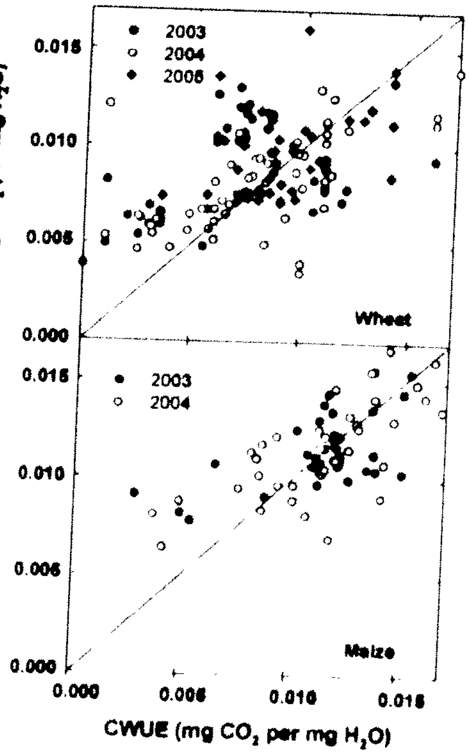

Fig. 8. Comparison of observed canopy water use efficiency (CWUE) over wheat and maize with values of CWUE predicted by multiple linear regressions given in Table 3 using values of crop water stress index and net radiation.

showed the model to be significant ($P < 0.01$, $R = 0.55$–0.64, Table 3) in 2004 and 2005 but not in 2003 ($P = 0.71$, $R = 0.18$). The regression model was highly significant ($P < 0.01$, $R = 0.63$–0.84) for both years in maize for data collected when net radiation was greater than 200 W m^{-2}. The plot of CWUE predicted from the regressions given in Table 3 vs. observed CWUE (Fig. 8) demonstrates the lower correlation between CWUE and the combination of net radiation and CWSI than was seen for LE and CO_2 fluxes.

4. Conclusions

The results of this study confirmed the large influence that viewed soil surface can have on CWSI calculated by the Jackson energy balance method. CWSI calculated under conditions in which the warm soil surface is viewed by the IRT are not useful for quantifying crop water stress, and methods should be employed to minimize viewed soil such as aiming the IRT across rows rather than parallel to the row direction.

The relationship between dT_{min} calculated by the Jackson energy balance method and VPD was confirmed to be linear and very similar to previously published empirically determined non-water-stressed baselines when net radiation levels were greater than 500 W m^{-2}. The value of dT_{min} at any given VPD decreased as net radiation decreased.

Both latent heat flux and CO_2 flux declined as CWSI increased when net radiation was greater than about 300 W m^{-2} for both wheat and maize. At lower net radiation levels latent heat flux and CO_2 flux may be more influenced by air temperature than by water availability and water stress. The response of CWUE to CWSI was more variable than the responses of latent heat flux and CO_2 flux, but could most often be characterized for both wheat and maize as CWUE declining with increasing CWSI when Rn was greater than 300 W m^{-2}.

This study demonstrated the utility of calculating CWSI continuously by the Jackson energy balance method under a wide range of net radiation conditions (300–700 W m^{-2}). Previous studies suggested that the usefulness of CWSI for detecting and quantifying water stress may be limited to semiarid areas of the world with mostly sunny, clear sky (high net radiation) conditions. The results of this study indicate that half-hourly averaged CWSI calculated during midday conditions when the soil surface is not viewed by the IRT and when net radiation is greater than 300 W m^{-2} should produce useful estimates of crop water stress which are correlated with latent heat flux and canopy photosynthesis. While the results are somewhat less than definitive, there appears to be ample evidence to warrant further investigation of the use of CWSI to quantify water stress in large field situations and to consider the use of CWSI in irrigation scheduling of wheat and maize in the important agricultural area of the North China Plain.

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